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Subterahertz Detection by High Electron Mobility Transistors at Large Forward Gate Bias

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Abstract

The electron delay time associated with the electron propagation across the FET gate barrier layer under high positive gate bias is expected to induce a dynamic negative differential conductance and enhance the growth of plasma waves in the channel [1]. This dynamic negative conductance is related to the phase shift between the current and voltage waveforms caused by the electron time delay during the electron tunneling through the gate barrier. We present experimental investigations of the plasma wave detector responsivity at 200 GHz and 600 GHz radiation for long channel AlGaAs/GaAs and AlGaInN/GaN based HEMTs at 8 K and 300 K. The appearance of detector response correlated with an increase of the injected gate current under the forward gate bias is reported for both types of the investigated devices. Our results confirm that a large gate current can enhance the excitation of plasma waves.

I. Introduction

Excitation of plasma waves in a channel of a high electron mobility transistor (HEMT) can be used for emission and detection of terahertz radiation [2-13]. When the electron mobility is sufficiently high, the HEMT channel serves as a resonant cavity for the plasma waves, and the detectivity has a maximum at the fundamental frequency of the plasma waves in the channel and its harmonics. When the electron mobility is relatively small, the plasma waves are overdamped, and the detection is nonresonant. Both types of the detection (resonant and nonresonant) have been observed [6, 8, 12, 13]. Recently, we analyzed dynamic behavior of the electron system in high-electron mobility transistors (HEMTs) associated with tunneling injection from the two-dimensional channel into the gate under forward bias. We showed that the propagation of the injected electrons across the barrier layer could result in the self-excitation of plasma oscillations in the HEMT [1]. This self-excitation is caused by the dynamic negative conductance that comes from the phase shift between the current and voltage waveforms resulting from the electron time delay. As another consequence of the same effect, we expect that the detectivity should have a peak at high

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gate bias when the gate current becomes large. In this paper, we report on the first observation of such detectivity peaks at large forward gate bias in GaAs and GaN-based HEMTs.

II. Experimental Results and Discussion

The detectors used in our experiments are long-channel AlGaAs/GaAs and AlGaN/GaN based High Electron Mobility Transistors (HEMTs). The gate length of GaAs HEMT is 2.5 μm. The separation between the gate and the source of GaAs HEMT is 2 μm, and the separation between the gate and the drain is 7 μm. The gate length of GaN HEMT is about 1.5 μm. For low temperature measurements we used a closed cycle compressor based cryostat with a temperature controller. The detector temperature was stabilized in the temperature range from 8 K to 300 K. The detectors were exposed to the 200 and 600 GHz radiation from two different Gunn oscillator systems.

The current voltage characteristics of the GaAs and GaN devices at $T = 8$ K are shown in Fig.1 a and Fig.1 b, respectively.

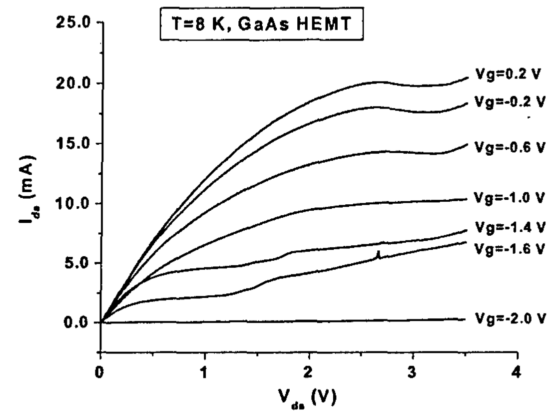


Fig.1 (a) The current-voltage characteristics of GaAs HEMT at 8K

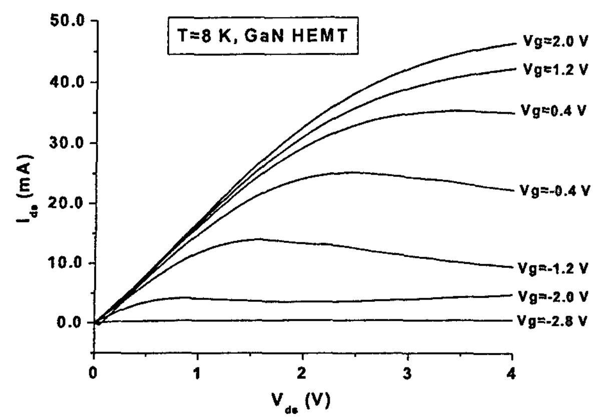


Fig.1. (b) The current-voltage characteristics of GaN HEMT at 8K

The transfer characteristics of the GaN-based and GaAs-based devices are shown in Fig.2.

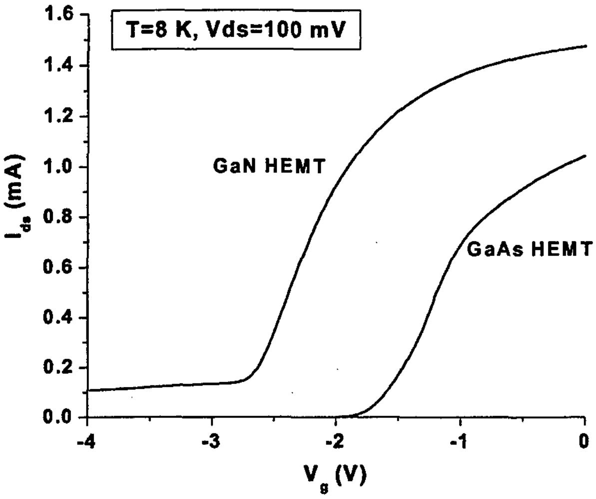


Fig.2. Transfer characteristics of GaAs and GaN HEMTs at 8K

As seen from Fig. 2, the threshold voltages of the devices are V_T=-2.8V for GaN HEMT and V_T=-1.7V for GaAs HEMT.

Fig. 3a shows the detector response of GaN HEMT detector exposed to 201 GHz radiation at 8 K.

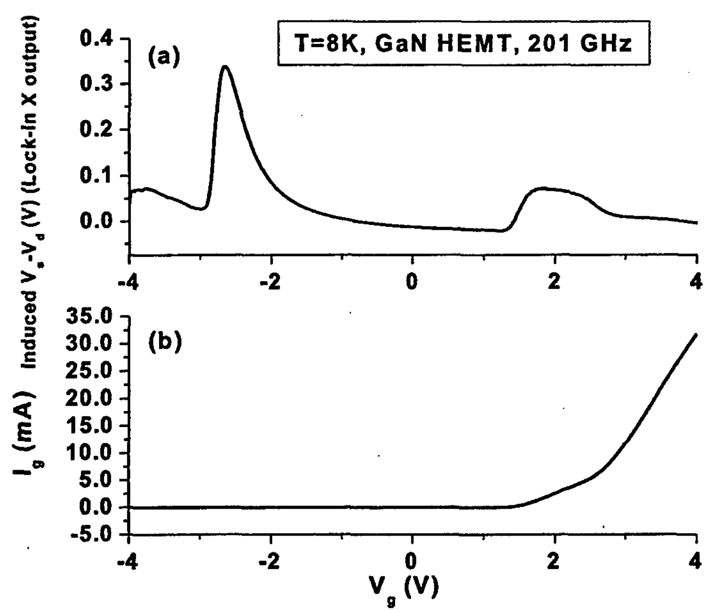


Fig. 3. (a) The GaN HEMT detector response to 201 GHz radiation at T=8 K and (b) Gate current versus gate voltage for the positive (forward) gate bias at 8 K.

One can observe two pronounced maxima. The first one near the transistor threshold –2.6V is due to non-resonant detection, which was extensively discussed in Ref. [12]. We attribute the second peak at V_g=2V to the new mechanism associated with tunneling or thermionic-field electron injection from the two-dimensional channel into the gate under the forward bias [1]. The current voltage characteristic of the gate barrier is shown in Fig.3 b. As can be seen from Fig.3 b the maximum of the detector signal under positive gate bias is correlated with the increase of the gate current.

Similar correlation between the detectivity increase and the gate current was observed for the GaAs-based transistor. The detector response for a few frequencies ranging between 188 GHz and 212 GHz is shown in Fig. 4.

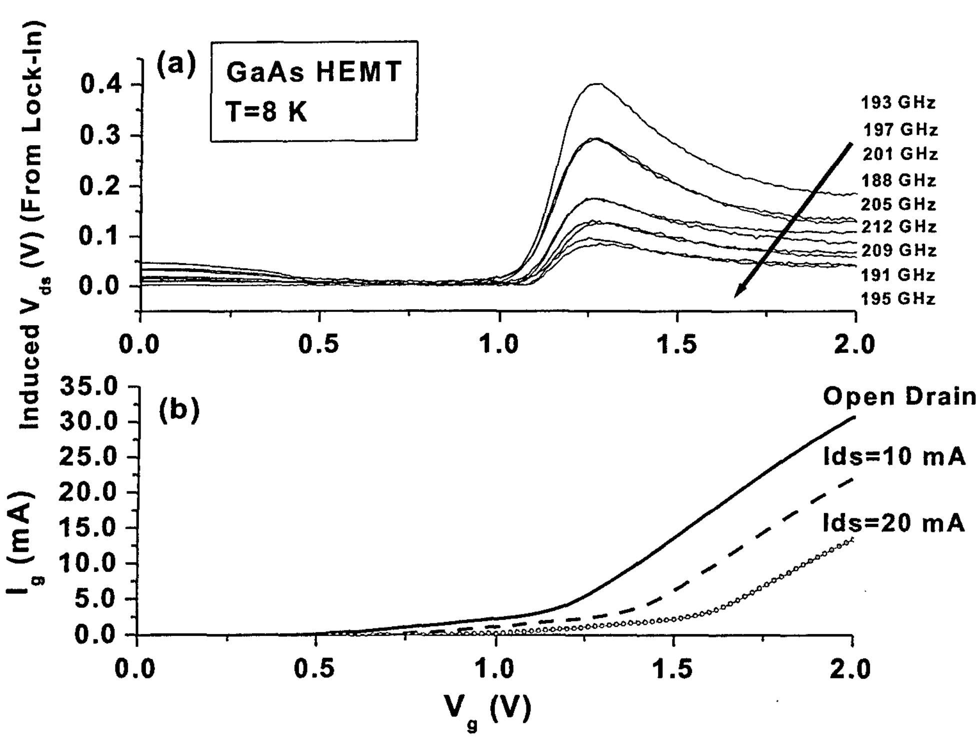


Fig. 4. (a) 188 GHz to 212 GHz radiation response of GaAs HEMT under large positive gate bias at 8 K and (b) Positive bias gate current voltage characteristics for GaAs HEMT.

The gate current voltage characteristic is shown in Fig. 4 b. From comparison of figures 4 a and 4 b, one can see that both the detector signal and the gate current start to increase (simultaneously) when the gate bias reaches +1V.

The GaAs detector response was also investigated as a function of the source drain current. The results are shown in Fig.5

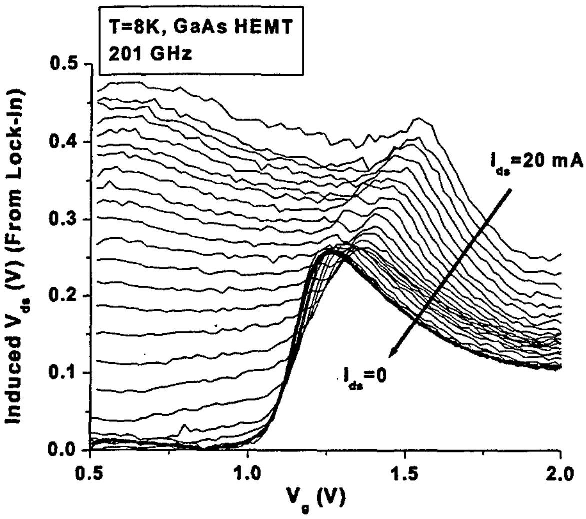
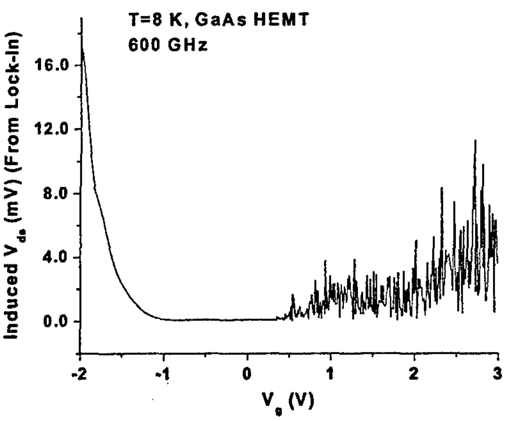


Fig. 5. 201 GHz radiation response of GaAs HEMT under large gate bias with DC drain current at 8K. I_{ds} increases from 0 to 20mA. The drain current step for I_{ds} in the range between 1mA and 20mA is equal to 1mA.

As seen from the Fig. 5, the higher is the drain current, the less pronounced is the maximum at positive gate bias (but the higher is the overall response). The gate current decreases with the increase of the drain current (see Fig. 4 b.). Therefore, the decrease at the maximum in Fig. 5 confirms the suggestion that it is related to the gate current [1].

We also performed the detection experiments for 600 GHz radiation. The results are shown in Fig 6a for GaAs HEMT and in Fig.6 b for GaN HEMT. For this frequency, only detection for negative gate voltages close to the threshold voltage was observed (see Ref. [12]). For positive gate voltages only noisy broadband signals were registered.



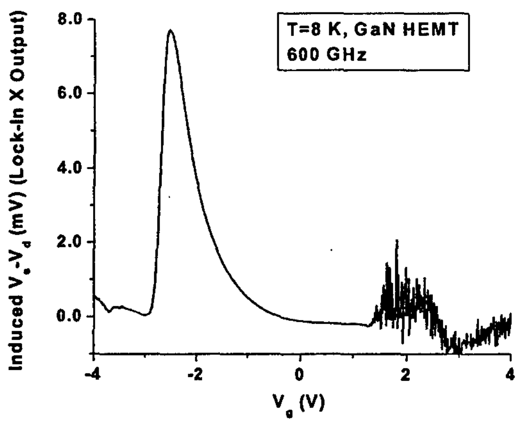


Fig. 6. (a) 600 GHz radiation response of GaAs HEMT at 8 K

Fig. 6. (b) 600 GHz radiation response of GaN HEMT at 8 K

One of the possible reasons can be that the resonant frequency of the plasma oscillations is much smaller than 600 GHz.

The fundamental frequency of the plasma oscillations is given by [3]:

$$f_0 = \frac{1}{4L}\sqrt{\frac{qU_0}{m}} \tag{1}$$

where m is the effective mass, L is the gate length, and $U_o = V_g - V_T$ is the gate voltage swing. The calculated dependence f_o versus U_o is shown in Fig. 7. The gate lengths for GaAs and GaN HEMTs in calculation are 2.5 μm and 1.5 μm, respectively. One can see that the 200 GHz resonant frequency lies well in our measurement range (V_g=0 to 4V) while 600 GHz is out of this range.

Two big dots in Fig. 7 are the measured peak positions of radiation responsivity for GaAs and GaN HEMTs at large gate bias, respectively. They are closer to the resonant frequency of 200 GHz than that of 600 GHz. The large width of the maximum at large gate bias means that the measurement frequency does not correspond to the resonant frequency and that the response (if it exists) is fairly broad.

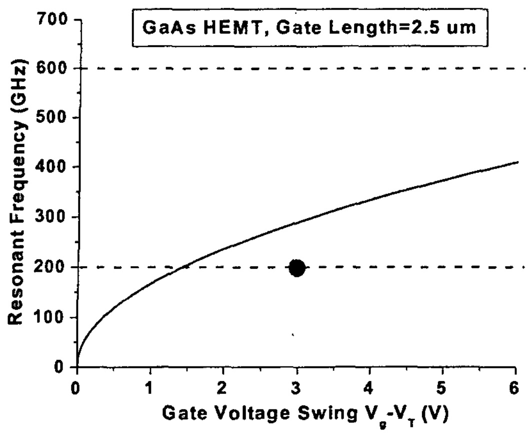


Fig. 7. (a) Resonant frequency f_0 versus U_o for GaAs HEMTs

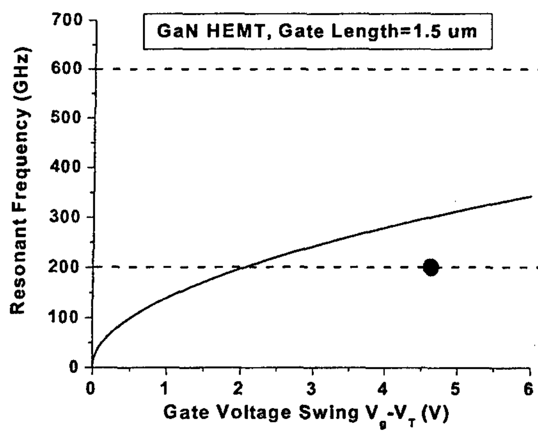


Fig. 7. (b) Resonant frequency f_0 versus U_o for GaN HEMTs

As shown in Fig.8, no response peaks at positive gate bias were observed at room temperature. Only the small non-resonant response (nearly 10 times smaller than that at 8K in Fig. 3 a) for negative gate bias close to the threshold voltage was observed. This decrease can be related to the decrease of the electron mobility (momentum relaxation time) at higher temperatures due to increased polar optical phonon scattering. However, our calculations using the theory developed in [3] indicate that the change of the electron mobility from 8,000 cm^2/V-s to 2,000 cm^2/V-s could only explain the decrease in response on order of factor of 2.

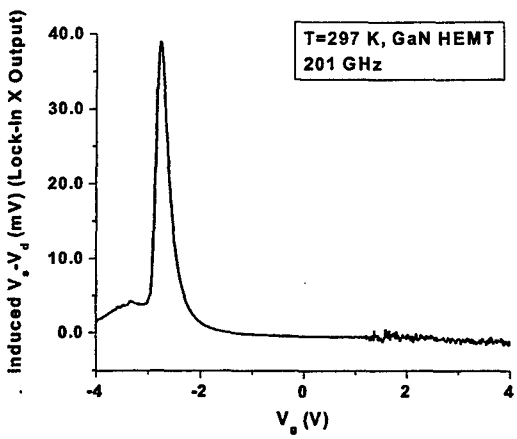


Fig. 8. 201 GHz radiation response of GaN HEMT at room temperature

III. Conclusion

We presented experimental investigations of the plasma wave detector responsivity at 200GHz and 600GHz radiation for long channel AlGaAs/GaAs and AlGaN/GaN based HEMTs at 8K and 300K. The enhancement of the responsivity at high positive gate bias was observed. We found that this enhancement, in both types of the devices, is correlated with the increase of the gate current under the forward gate bias. These results can be explained on the basis of the new theoretical model in which the plasma self-excitation can appear under condition of the high gate current.

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